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# EXPERIMENTAL INVESTIGATION OF THE DYNAMICS OF WATER REJECTION FROM A MATRIX TYPE OF HYDROGEN-OXYGEN FUEL CELL

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## ABSTRACT

An experimental study of water-rejection dynamics was conducted on a matrix type of hydrogen-oxygen fuel cell which employs a hydrogen stream to extract the product water. Step transients were introduced in the hydrogen inlet humidity and in the rate of electrochemical water production. The resulting water-rejection transients were measured as changes in hydrogen outlet humidity. The transient response data were compared to the responses of a mathematical model developed for a Bacon type of cell. Data are presented which illustrate the effects that various initial operating conditions have on the outlet humidity responses for step transients in both inlet humidity and the rate of water production.

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## SUMMARY

An experimental study of water-rejection dynamics was conducted on a matrix type of hydrogen-oxygen fuel cell which employs a hydrogen stream to extract the product water. The investigation was conducted by introducing step transients in the inlet stream humidity and in the rate of electrochemical water production. The resulting water-rejection transients were measured as changes in outlet-stream humidity.

For steps in inlet humidity a first-order mathematical model developed for a Bacon-type (free electrolyte) cell (ref. 1) provided a rough approximation of the matrix-cell water-rejection process; however, effects other than first-order were also present in the matrix-cell response data. For step transients in the rate of water production an overshoot occurred in the outlet-stream response, thus negating the use of the Bacon-cell model to approximate the matrix-cell water-rejection process. The experimental data show the water-removal process to be nearly linear for steps in the humidity of the inlet stream but nonlinear for disturbances in the rate of water production. Also, data are presented which illustrate the effects that various initial operating conditions have on the outlet humidity responses for step transients in both inlet humidity and load current.

## INTRODUCTION

The product of the electrochemical reaction in hydrogen-oxygen fuel cells is water. This water must be removed from the cells in order to prevent an excessive increase in electrolyte volume which could cause failure of the fuel cells by flooding the electrode and reactant supply system. In addition, removal of water at a controlled rate provides an effective means of maintaining the electrolyte concentration within the operating range for which the cells were designed. One water-removal technique employs a diffusion process to transport the water from the point of formation within the cell to an

extraction system, such as a circulating gas stream. By controlling the stream conditions of temperature, pressure, flow rate, and humidity, the flow of water out of the cell is regulated and the electrolyte concentration is maintained in the allowable range. This water-removal technique is used with the free-electrolyte, Bacon-type cells for the Apollo mission and is being considered for use with matrix-type (contained-electrolyte) cells currently under development.

Experimental and analytical studies of the dynamics of water rejection in the Bacon cell have been conducted at the Lewis Research Center, and the results of these studies appear in reference 1. These studies were conducted as a first step in gaining an understanding of the processes involved in water removal by diffusion to a circulating gas stream. Such understanding, of course, is needed in the design of fuel-cell system controls.

As part of a continuing program a study of the dynamics of water rejection in a matrix-type cell is being conducted at Lewis. The experimental information that has been acquired from this study is presented in this report. The matrix cell studied used hydrogen as the circulating gas stream. American Cyanamid (type AB-40) high-current-density electrodes (ref. 2) were used as both anode and cathode, and the electrolyte was an aqueous solution of potassium hydroxide which was contained in an asbestos matrix. The cell was operated at a temperature of $200^{\circ}$ F (366 K) and a pressure of 8 psig (5.52 $N/cm^2$ gage).

In the test program, step disturbances were introduced in the water-vapor-to-hydrogen mass ratio (humidity) of the inlet-stream and in the cell load current (rate of water production). Also, a frequency-response test was run in which sinusoidal variations in the inlet-stream humidity at various frequencies were introduced. The transients resulting from the various input disturbances were measured as changes in the mass flow ratio of water vapor to hydrogen at the fuel-cell outlet. A fluidic humidity sensor was used for the measurement of the outlet mass ratio (ref. 3).

# APPARATUS AND INSTRUMENTATION

## Fuel Cell

A schematic diagram of the type of matrix cell tested and the cell assembly are shown in figures 1 and 2. In this cell an aqueous electrolyte with a potassium hydroxide concentration of approximately 50 percent by weight is contained by a matrix of 0.030-inch- (7.6-mm-) thick Johns-Manville fuel-cell asbestos. The electrodes (American Cyanamid type AB-40) consist of a nickel screen coated with a mixture of teflon and platinum black catalyst. The electrodes are 0.030-inch (7.6-mm) thick and have a surface area of approximately 36 square inches (232 $cm^2$). The reactant

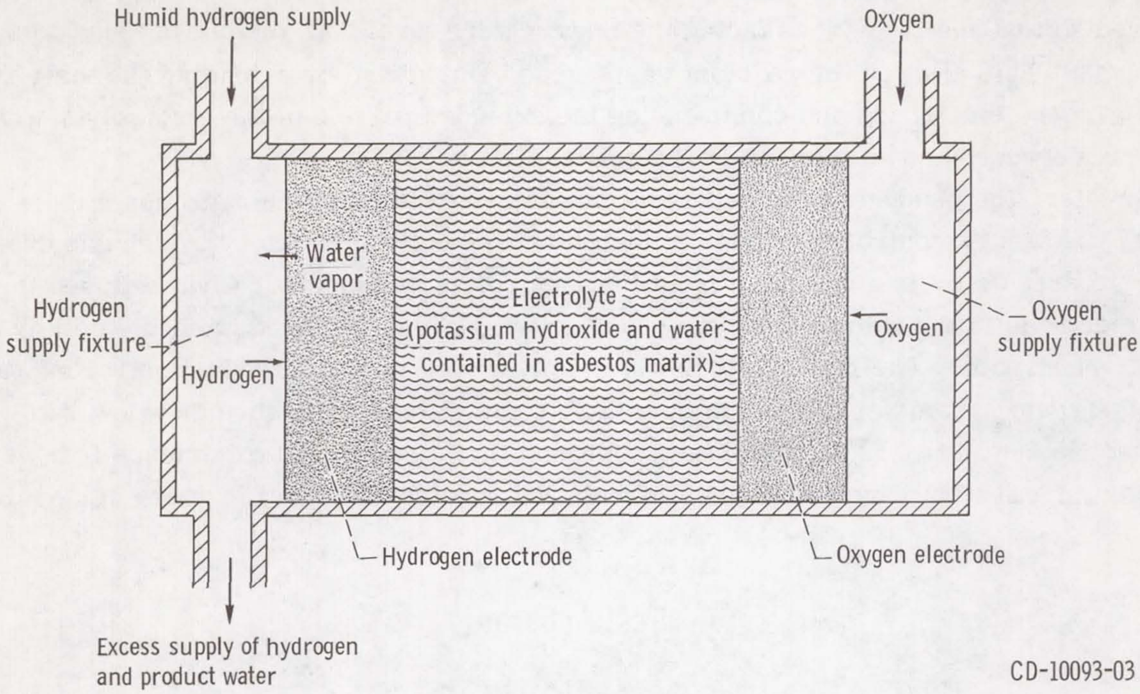


Figure 1. - Schematic of fuel cell used in tests.

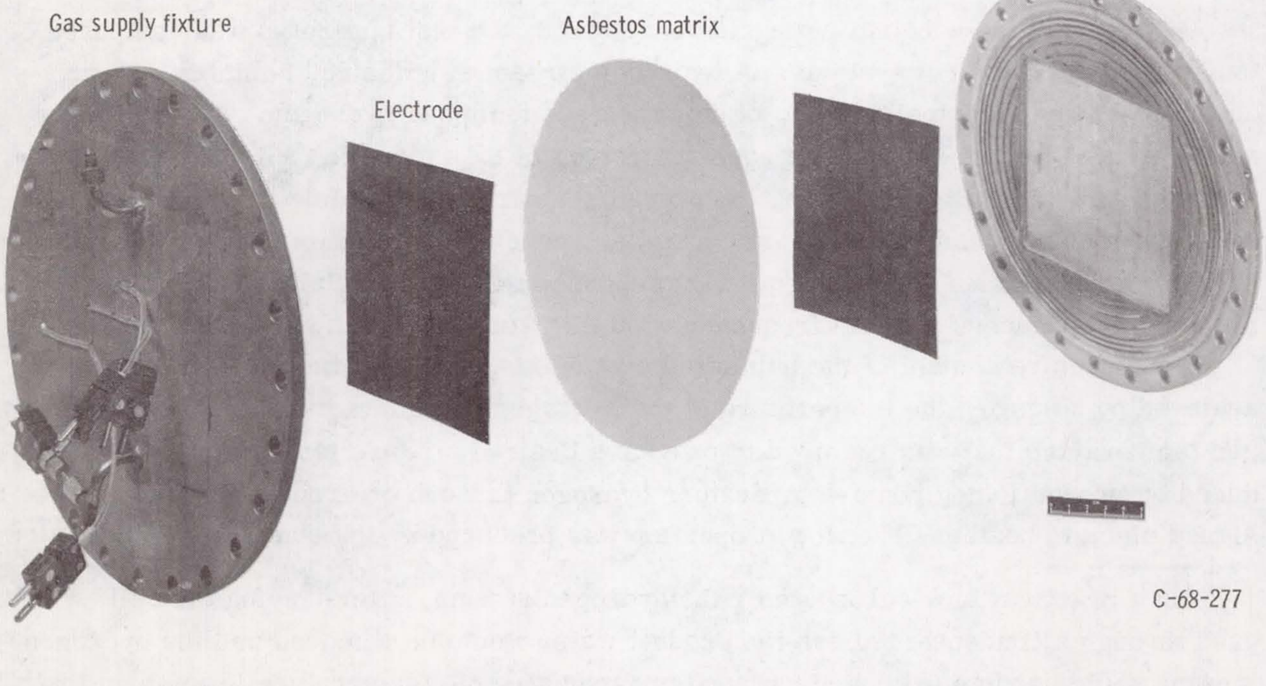


Figure 2. - Fuel-cell assembly.

supply test fixtures were designed such that, when installed, the electrodes were recessed so that their surfaces facing the matrix were level with the mating surfaces of the fixtures. This allowed the reactant gas seal to be achieved by extending the matrix material past the electrodes and compressing the extended portion of the electrolyte-wetted matrix between the two fixtures in the cell assembly.

Water, the product of the cell reaction, is removed from the hydrogen side of the cell by flowing a controlled excess of humid hydrogen through the hydrogen gas chamber. The product water is evaporated from the electrolyte and in vapor form diffuses through the electrode to the hydrogen supply chamber where it is removed from the cell by the reactant stream. The rate at which water is removed is regulated by controlling the inlet-stream parameters: stream humidity, temperature, pressure and flow rate. The stream is humidified to simulate the conditions that a cell would experience if it were installed in a system which employs a circulating reactant stream for water removal.[1]

## Test Apparatus

A remotely controlled test apparatus was designed with the capability of supplying a test fuel cell with a conditioned hydrogen-steam mixture. The apparatus provides control of the stream parameters of temperature, pressure, flow rate, and humidity plus the capability to produce controlled perturbations in any one of these parameters while holding all others at their initial set points.

As shown in the schematic diagram of figure 3, the test apparatus was composed of four closed-loop control systems. A hydrogen stream at a desired humidity was produced by mixing a controlled ratio of superheated steam and hydrogen. The ratio was set by controlling the flow rate of each component of the mixture. This component flow control was achieved by regulating the pressure upstream of a sonic flow orifice in both the hydrogen and steam lines. Fast controller response was attained by using electrohydraulically actuated valves (frequency response, flat up to 10 Hz), strain-gage pressure transducers (natural frequency, 600 Hz), and a minimum of tubing volume.

Temperature control of the humidifed stream at the inlet of the fuel cell was achieved by adjusting the temperature of the hydrogen portion of the stream. The hydrogen temperature that was required to provide a desired mixture temperature was produced by proportioning room-temperature hydrogen through or around a specially designed electric heater. The flow proportion was produced by the controller which acted

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[1]In a practical fuel-cell system, the hydrogen stream, after leaving the cell, would pass through a condenser. Here the product water would be removed and the hydrogen stream would become saturated with water vapor at some temperature lower than that of the cell. The stream would then return to the cell in this condition.

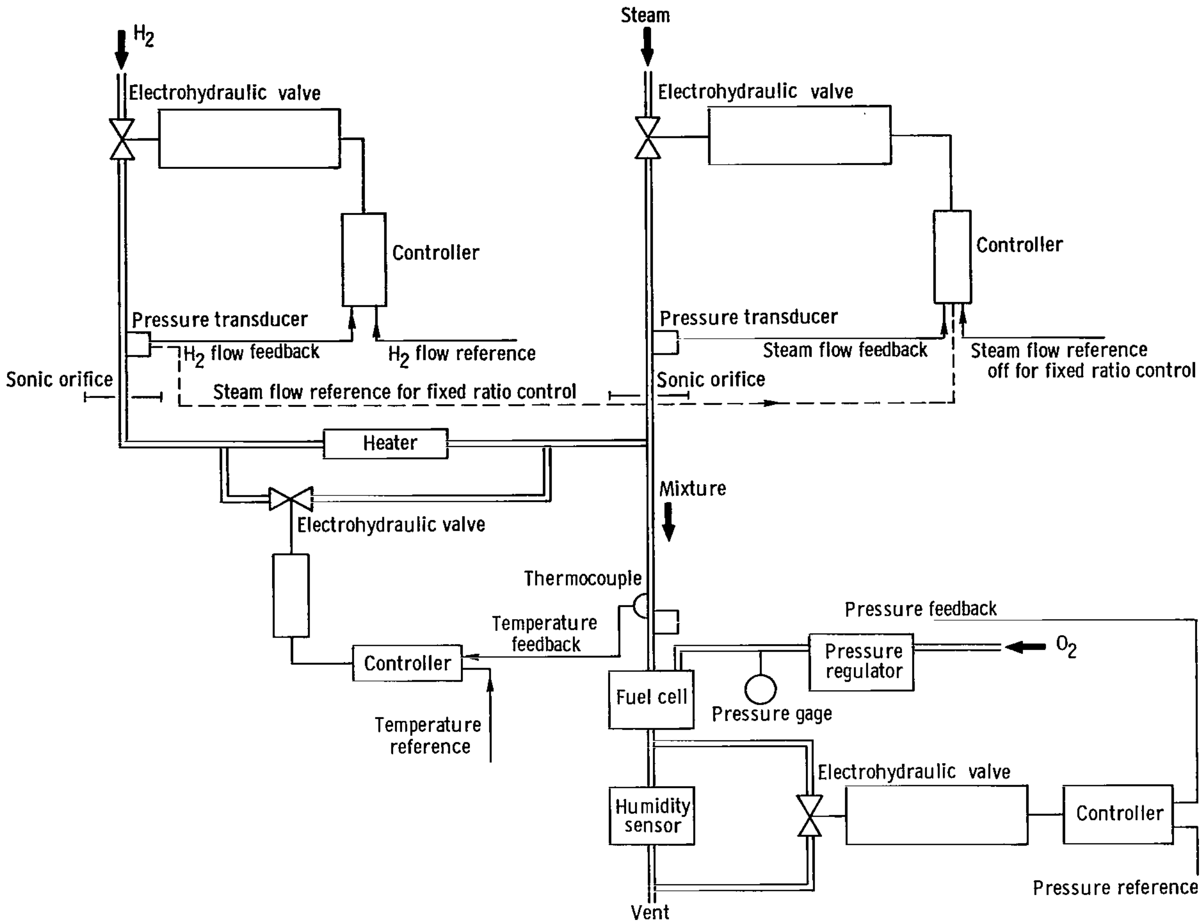



Figure 3. - Schematic diagram of fuel-cell dynamics test rig.

to adjust the valve setting in the heater bypass line such that the desired stream temperature (controller input) and the actual mixture temperature (controller feedback) were equal.

Since the hydrogen-stream pressure drop from the cell inlet to outlet was negligible for the flows at which the cell was operated, cell pressure control was attained by controlling the position of the vent-line valve located downstream of the cell.

Integral-proportional control, which was used in the various control circuits, was achieved by building up the controller circuits on a transistorized analog computer. The computer was used because it provided a concentration of highly accurate, flexible, drift-free electronic equipment, which lends itself well for use in controller circuitry.

## Instrumentation

The fuel cell was instrumented with thermocouples which were installed at various locations on the surface of the gas supply fixtures, as well as in the hydrogen stream at both the inlet and outlet of the cell.

To obtain a temperature profile of the heated test apparatus, thermocouples were installed on the electrohydraulic control valves and at intervals along the length of the rig tubing. A thermocouple was inserted into the flow upstream of the steam sonic orifice. This temperature served as a reference by which to manually set the steam superheater temperature and, thereby, to maintain the steam at the temperature for which the orifice was calibrated.

The instrument used to measure the humidity (steam-to-hydrogen mass ratio) of the fuel-cell outlet stream was a continuous-reading device. The basis of the instrument is a fluidic oscillator with a frequency of oscillation sensitive to the molecular weight or mass ratio of the stream in question. The instrument displayed good accuracy (±2 percent) and a frequency response which was flat up to at least 3 hertz (ref. 3).

The recording equipment that was used included the following components:

(1) A digital voltmeter to check pertinent fuel-cell and test apparatus parameters during operation

(2) Strip-chart recorders to record stream input and transient data, selected cell temperature, and cell power data

(3) A profile monitor to provide a visual display of 20 test rig temperatures which were used as references in making test apparatus heater settings

(4) A digital counter to provide a visual check of the frequency of oscillation of the fluidic humidity sensor during operation.

## Electrolyte Concentration Analyzer

An analog computer program was developed to provide a continuous calculation of the cell electrolyte concentration during operation. The program, the circuit for which is shown in figure 4, is based on the conservation of mass of water in the electrolyte. The inputs to the program are voltage analogs of the cell operating current, inlet-stream water-vapor flow rate, inlet-stream hydrogen flow rate, humidity sensor oscillation frequency, and the mass of pure potassium hydroxide present in the electrolyte mixture.

The conservation-of-mass equation states that the time rate of change of the mass of water in the electrolyte equals the rate of water flow into the cell plus the water

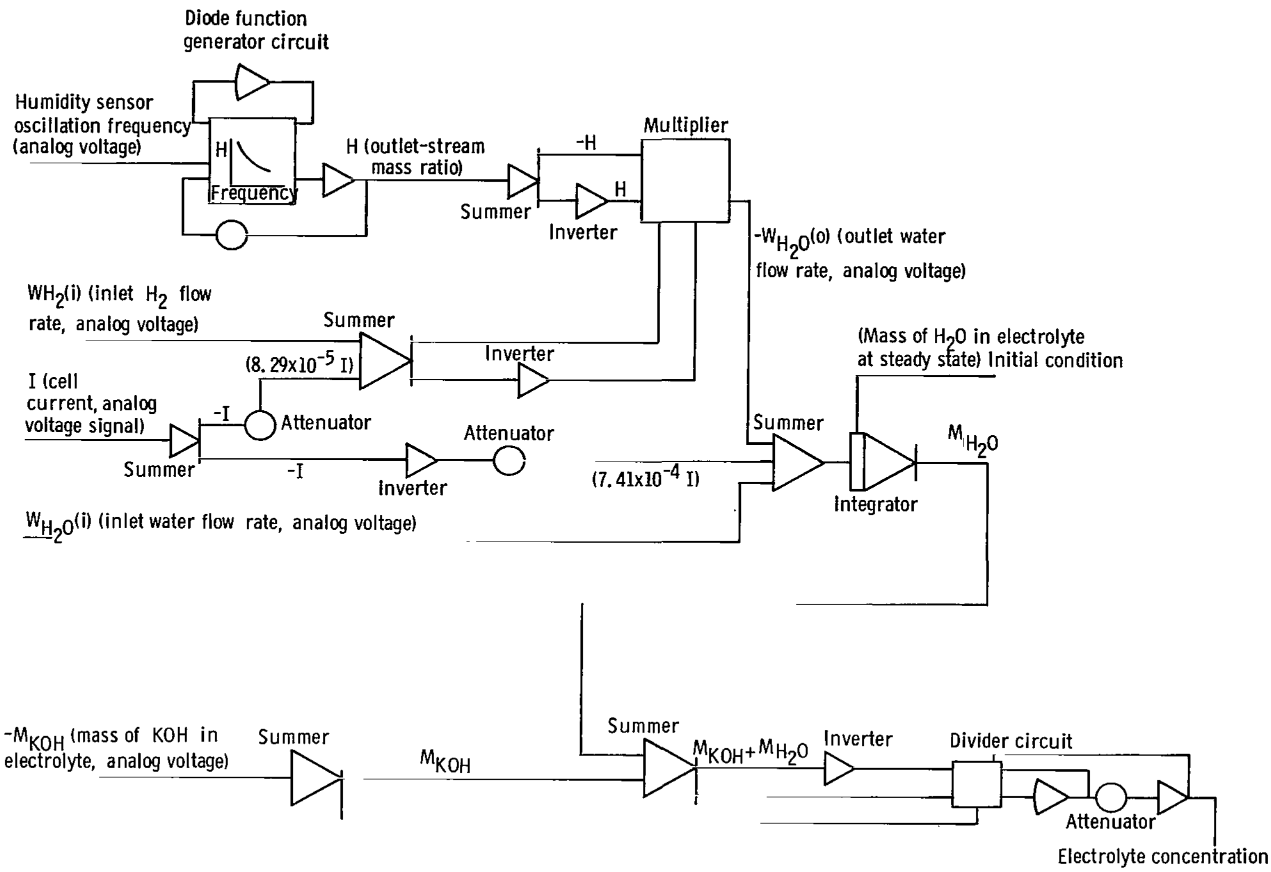


Figure 4. - Computer circuit for electrolyte concentration calculation.

formed by the cell minus the flow of water out of the cell. As programmed on the computer, the equation can be expressed as

$$\frac{dM_{H_2O}}{dt} = W_{H_2O}(i) - W_{H_2O}(o) + 7.41\times10^{-4}\ I$$

where $M_{H_2O}$ represents the mass of water present in the electrolyte at any instant of time t, $W_{H_2O}(i)$ is the flow rate of water in the humid hydrogen stream entering the cell, and $W_{H_2O}(o)$ is the rate of flow of water in the hydrogen stream leaving the cell. The term $7.41\times10^{-4}$ I represents the rate at which water is produced by the cell reaction where I is the cell current and the quantity $7.41\times10^{-4}$ is the Faraday constant. The signal for the rate of flow of water in the outlet hydrogen stream $W_{H_2O}(o)$ was obtained by multiplying the flow rate of pure hydrogen in the outlet stream by the outlet-stream

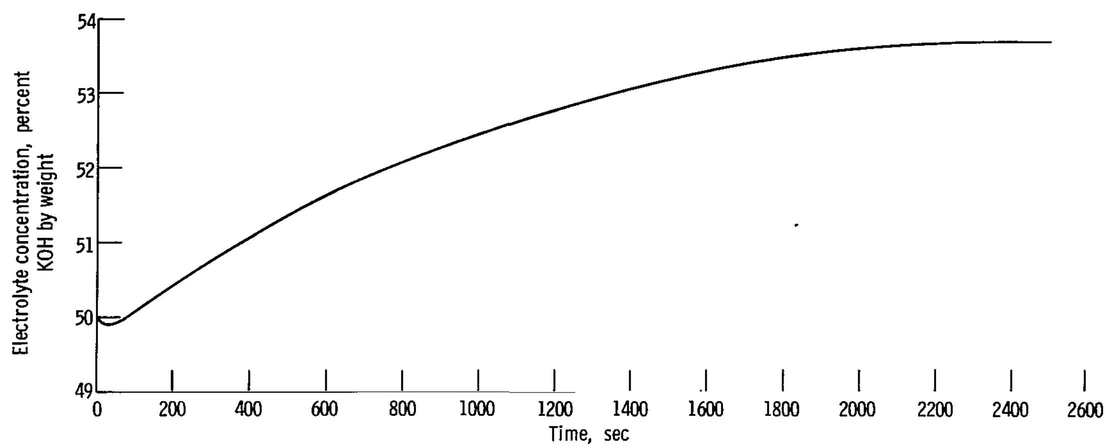



Figure 5. - Analog program concentration calculation for a step increase in load current (rate of water production).

mass ratio (humidity). This humidity signal was obtained by supplying the sensor oscillation signal to a diode function generator which was set up with a sensor calibration curve relating oscillator frequency to stream humidity. The signal representing the rate at which water was formed by the cell reaction was attained by multiplying the cell current by a constant. The term representing the flow of water into the cell was taken from the test apparatus, where it is one of the hydrogen-stream parameters being controlled.

Thus, by summing the three water-flow-rate terms and integrating, the program calculated the mass of water present at any time t. By dividing this mass by the total electrolyte mass, the electrolyte concentration was obtained. A typical change in concentration as calculated by the program is shown in figure 5.

## TEST PROCEDURE

With the cell gas supply chambers purged with nitrogen, the oven in which the cell was installed was heated to bring the cell to operating temperature $200^{\circ}$ F (366 K). Once operating temperature was attained, the reactants were introduced and the load was applied. The humidity at which the hydrogen was supplied to the cell was dictated by the steady-state electrolyte concentration desired for a particular test; namely, to produce a more concentrated electrolyte, a mixture was circulated at a humidity lower than that required to hold the electrolyte at the concentration at which the cell was constructed (approximately 50 percent). A steady-state operating condition was realized when the startup transients in the continuously monitored parameters of cell temperature, voltage, and current were damped out and when the concentration calculation program indicated a constant concentration.

Once steady-state was attained, dynamic tests were conducted by disturbing the inlet hydrogen humidity or the rate of water production of the cell while recording the transient response as a change in the outlet hydrogen humidity. The water-production disturbances were step functions which were introduced as changes in cell load current by stepping the load resistance. The disturbances in inlet hydrogen humidity were fast ramp functions that were produced by ramping the flow rate of steam with the test apparatus steam flow control system. Since the speed of these input ramps was fast compared with the speed of the resulting transients, these data could also be assumed to be those of step response. For both types of transients, perturbations of various magnitudes were run with the cell at the same initial operating conditions. Similarly, transient tests were run in which identical disturbances were introduced with the cell at various initial operating conditions.

After a transient was introduced, the effects that the changing cell parameters, such as temperature and electrolyte concentration, had on the load current were negated by adjusting the load resistor setting to produce a constant load current. The result of this was to produce the desired condition in which the rate of water production was held constant during the reestablishment of a steady-state operating condition.

A frequency-response test was run in which the humidity of the hydrogen - water-vapor mixture being supplied to the fuel cell was varied sinusoidally over a range of frequencies. The humidity variation was produced with the test apparatus by sinusoidally varying the flow rate of the steam prior to mixing it with the dry hydrogen. The resulting sinusoidal response data were read from the fluidic humidity sensor and recorded on a strip-chart recorder. From the input and output sine waves, amplitude attenuation and phase shift data were obtained for the range of frequencies tested.

# RESULTS AND DISCUSSION

## Inlet Humidity Transients

A transient response of cell outlet water-vapor flow rate to a step in the water-vapor flow rate in the inlet stream is shown in figure 6. The response reflects the readjustment of the electrolyte concentration to the equilibrium value corresponding to the increased stream humidity. For the transient shown in this figure the cell was operated at open circuit, and no water was being produced. Thus, the inlet water-vapor flow rate was equal to the outlet water-vapor flow rate at both the initial and final steady-state conditions. The shaded area between the inlet flow step and the outlet flow response represents the mass of water absorbed by the electrolyte. These data depict an increase in the concentration of water in the electrolyte of approximately 5 weight

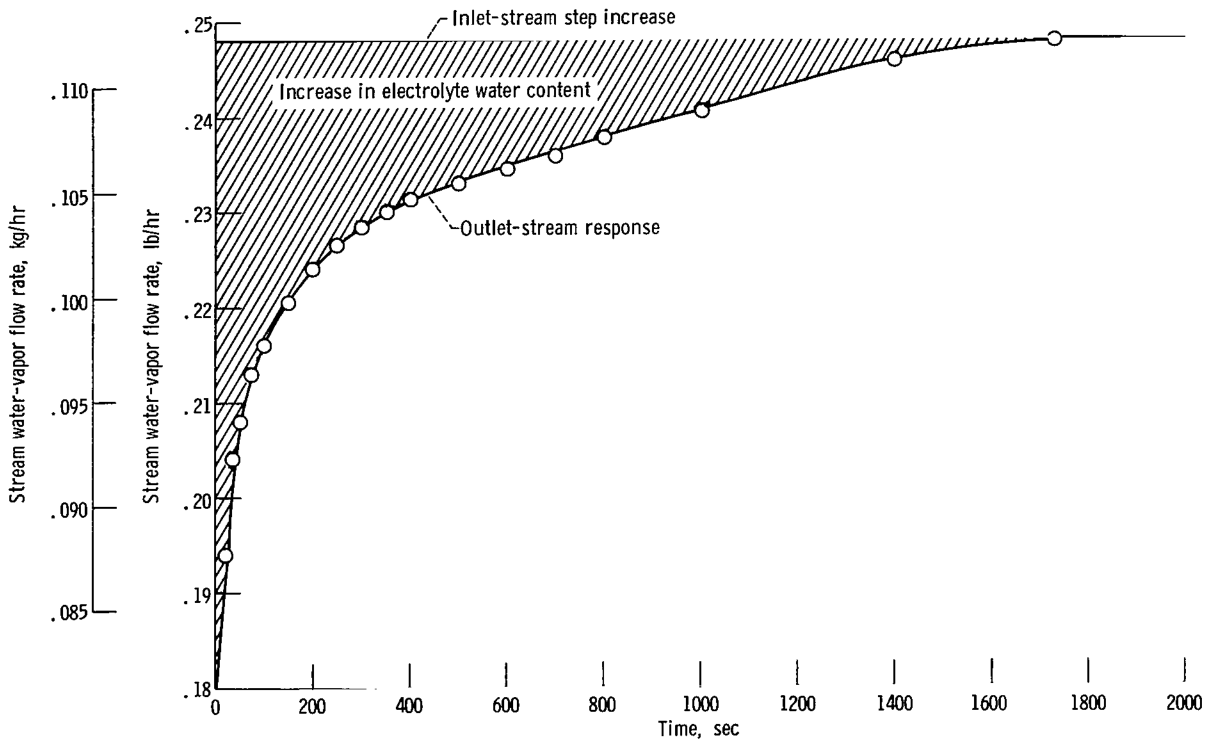



Figure 6. - Transient response of water-vapor flow rate of cell outlet stream to step increase in inlet-stream water-vapor flow rate. Operating conditions: cell power, 0; open circuit; inlet-stream hydrogen flow, 0.12 pound per hour (0.05 kg/hr).

percent as the result of the step in inlet-stream water-vapor flow rate from 0.18 to 0.248 pound per hour (0.08 to 0.11 kg/hr). This flow rate disturbance produced a step in the inlet-stream water-vapor-to-hydrogen mass flow ratio from 1.5 to 2.07.

To check the linearity of the matrix-cell water-rejection mechanism, humidity steps of three different magnitudes were introduced with the cell at the same initial operating conditions. To provide a basis for comparison, the response curves for these transients were normalized by plotting each data point as a ratio of the change in outlet-stream humidity (mass flow ratio) at any time to the total change between the initial and final equilibrium values. The normalized response curves for the three humidity steps are plotted in figure 7. Since the range of magnitudes covered by the three transients is sizeable while the deviation between the response curves is small, the water-rejection process can be assumed to be nearly linear for disturbances in hydrogen-stream inlet humidity.

For steps in inlet-stream humidity, the effects that the pretransient operating conditions have on the outlet humidity response are illustrated in figures 8 to 10. To illustrate the effects that an increased initial flow rate of the hydrogen portion of the inlet stream has on the outlet humidity response, two transients were run in which a

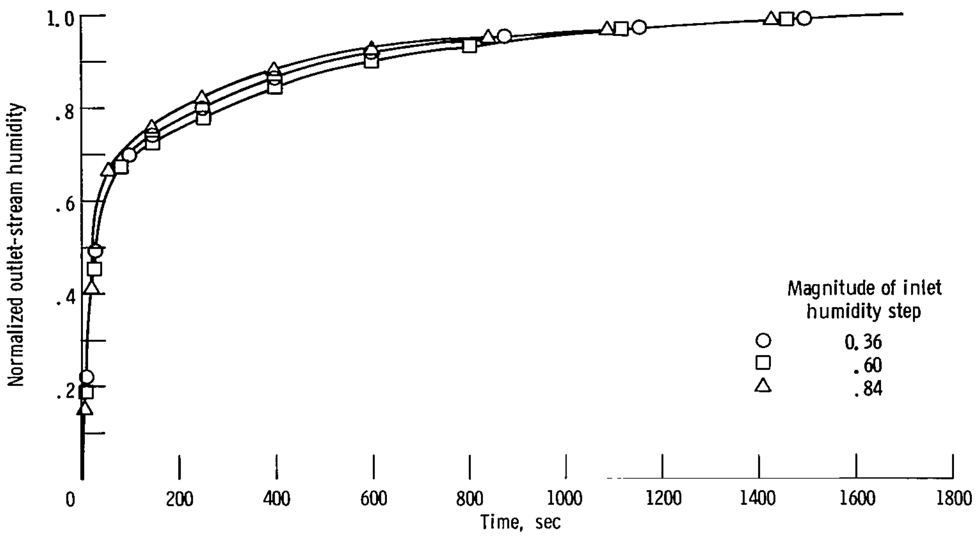



Figure 7. - Transient response of hydrogen outlet-stream humidity to various sized steps in inlet-stream humidity. Operating conditions: inlet-stream hydrogen flow, 0.12 pound per hour (0.05 kg/hr); inlet-stream initial humidity, 1.9; cell load current, 41 amperes.

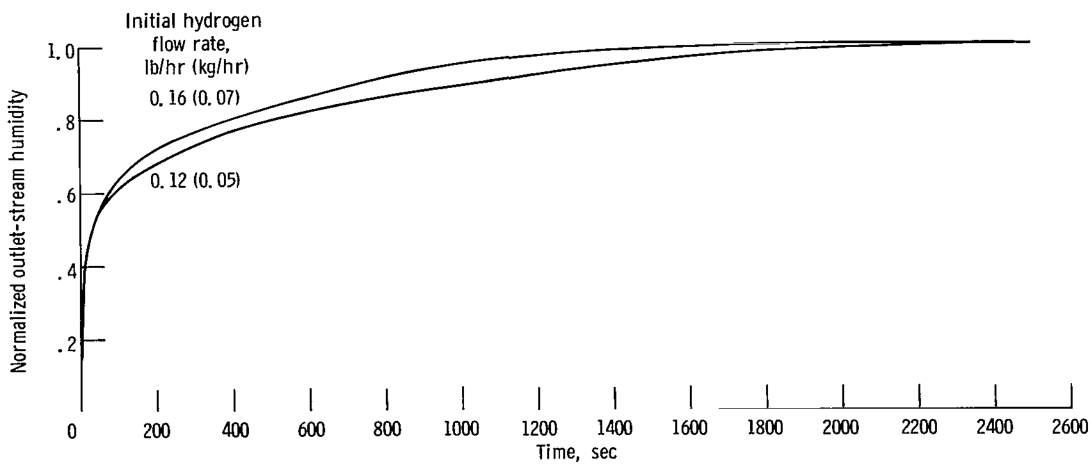



Figure 8. - Comparison of response of outlet-stream humidity to step in inlet-stream humidity from 1.5 to 2.0 for different initial hydrogen mass flow rates. Operating condition: cell load current, 41 amperes.

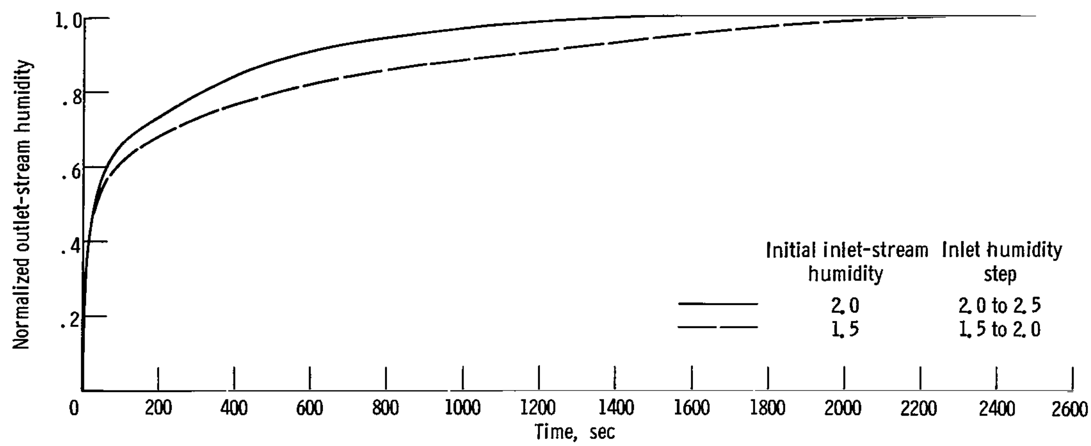



Figure 9. - Comparison of response of outlet-stream humidity to step in inlet humidity for different initial inlet humidities. Operating conditions: inlet-stream hydrogen flow, 0.12 pound per hour (0.05 kg/hr); cell load current, 41.2 amperes.

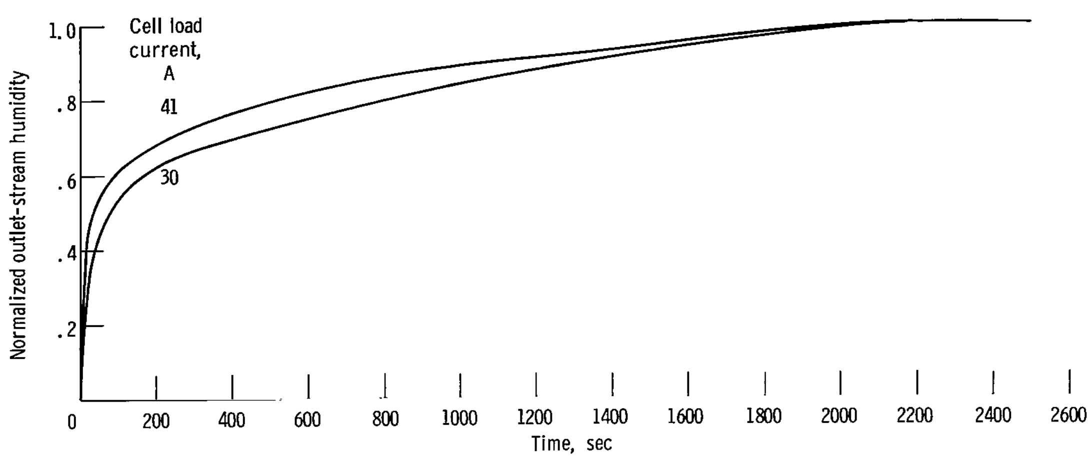



Figure 10. - Comparison of response of outlet-stream humidity to step in inlet humidity from 1.5 to 2.0 for different cell load currents. Operating condition: inlet-stream hydrogen flow, 0.12 pound per hour (0.05 kg/hr).

step in inlet humidity was introduced from the same initial value of humidity but for different initial hydrogen mass flow rates; one at 0.12 pound per hour (0.05 kg/hr) and the other at 0.16 pound per hour (0.07 kg/hr). The outlet-stream humidity responses of these two transients are plotted in figure 8. This figure shows that by increasing the initial hydrogen flow rate at constant humidity, the wetting effect on the electrolyte is less pronounced, and the response curve achieves steady-state faster.

The two transients shown in figure 9 illustrate the effects that an increased initial stream humidity has on the outlet humidity response. The mass flow of hydrogen for both transients was held constant at 0.12 pound per hour (0.05 kg/hr), while the initial humidity of one case was set at 1.5 and the other at 2.0. In general, the same effects

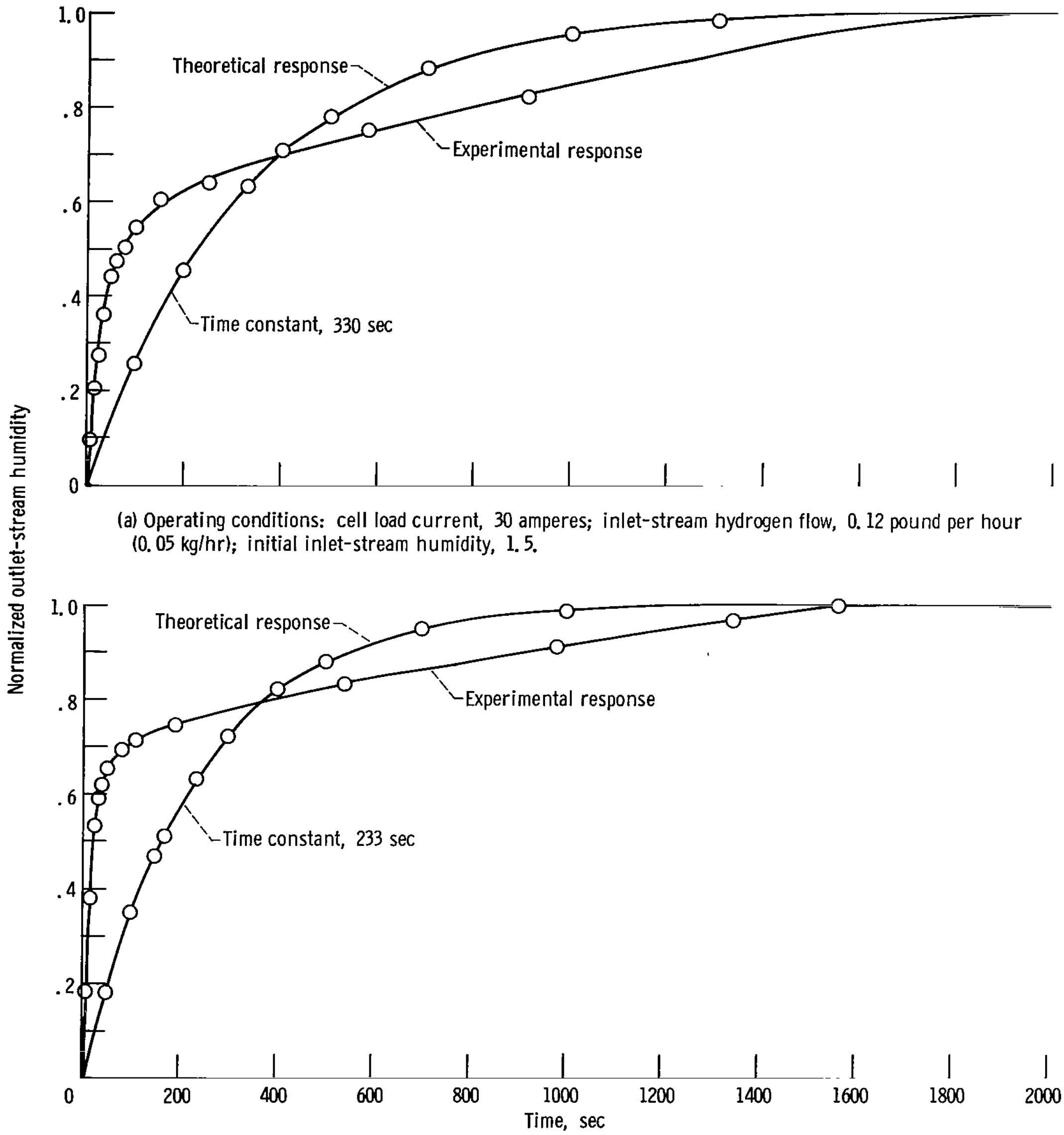
are noted as in the increased initial flow rate case (fig. 8). Increasing the initial humidity produces a decrease in the wetting effect on the electrolyte and an increase in the speed of the transient response.

The effect of pretransient cell load current on the outlet humidity response for a step in inlet humidity is shown in figure 10. This figure illustrates the responses of two inlet humidity transients introduced at the same initial stream conditions for initial load currents of 30 and 41 amperes. As for the cases of increased initial stream flow rate and increased initial humidity, the increase in the pretransient load current is seen to produce an increase in the speed of the transient response of outlet humidity and a decrease in the wetting effect on the electrolyte.

The matrix-cell water-transport process was compared to the theory developed for the Bacon-type cell (ref. 1). For two of the experimental inlet humidity transients, theoretical responses were calculated by substituting the matrix-cell parameters into the first-order Bacon-cell mathematical model. The cases chosen represent the two extremes in response speed obtained by varying the initial operating conditions. The experimental response and the corresponding calculated responses are compared in figure 11. The comparisons show that the responses of the first-order mathematical model provide as good a fit to the experimental data as could be provided by any first-order curve. Also, the fact that the agreement shown for the faster response case (fig. 11(b)) is as good as the agreement shown for the slowest response case (fig. 11(a)) indicates that the initial-condition effects controlling the speed of the experimental response are represented in the mathematical model. However, the observed deviations between the experimental and calculated curves of figure 11 indicate that additional effects other than first-order, are present in the experimental responses. Therefore, the Bacon-cell model provides only a rough approximation of the matrix-cell water-rejection process.

Log-magnitude and phase-shift plots of experimentally obtained outlet- to inlet-humidity frequency-response data are presented in figure 12. The non-first-order effects observed in the comparison of the matrix-cell and Bacon-cell model step responses are also in evidence in the frequency-response data. These effects are illustrated by noting the deviation between the slope of the log-magnitude plot and the line with a slope of 20 decibels per decade which is drawn for frequencies greater than 0.05 radian per second (one decade in frequency beyond the 3-db attenuation point of the data). If it were first-order, the log-magnitude plot would have the slope of this line for frequencies higher than 0.05 radian per second.

The speed of the response of the water-transport mechanism of the matrix cell was found to be faster than that of the Bacon-type cell. This is illustrated for figure 13 in which the slowest inlet humidity step response available for the matrix cell (open circuit, low initial flow, low initial humidity) is compared with the fastest Bacon-cell response available from the investigation reported in reference 1. For the data shown

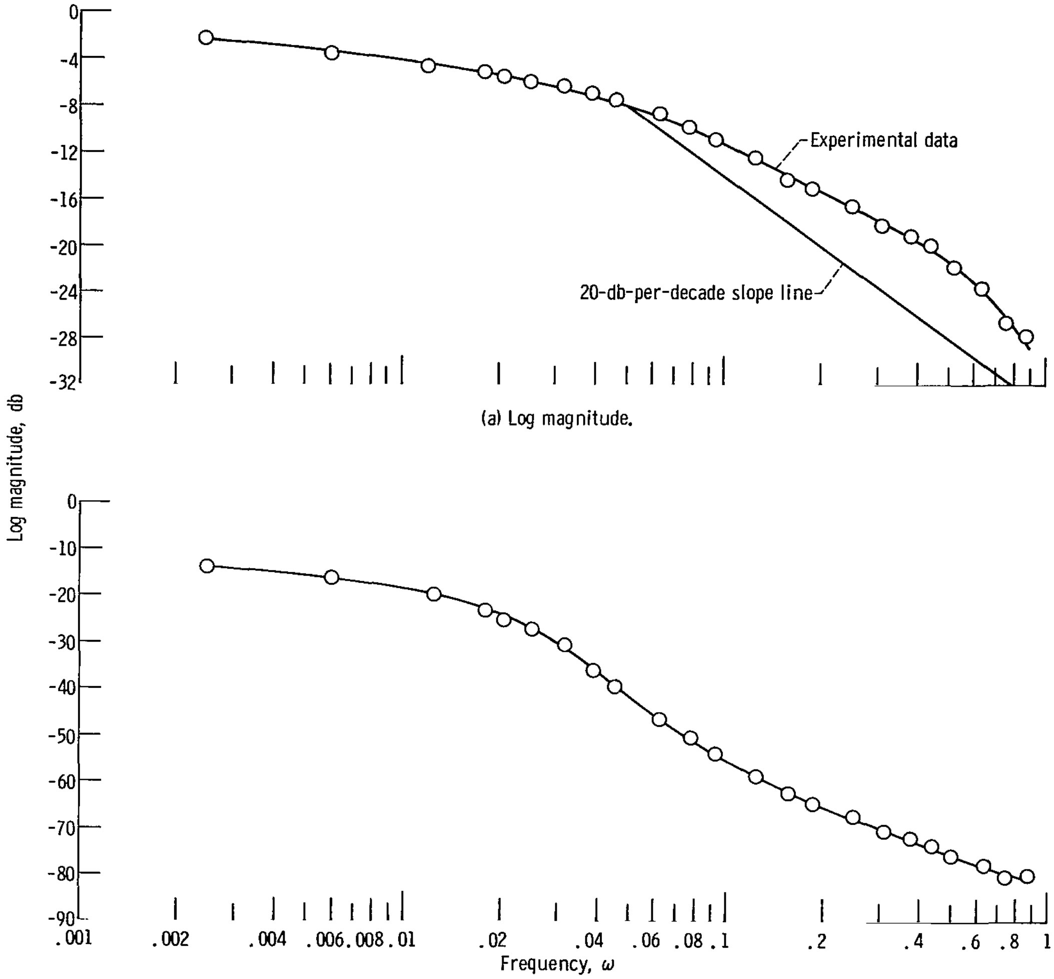



(a) Operating conditions: cell load current, 30 amperes; inlet-stream hydrogen flow, 0.12 pound per hour (0.05 kg/hr); initial inlet-stream humidity, 1.5.



(b) Operating conditions: cell load current, 54 amperes; inlet-stream hydrogen flow, 0.16 pound per hour (0.07 kg/hr); initial inlet-stream humidity, 2.0.

Figure 11. - Comparison of theoretical and experimental transient response to step increase in inlet-stream humidity.




(b) Phase shift.

Figure 12. - Outlet- to inlet-humidity frequency response. Operating conditions: cell load current, 40 amperes; inlet-stream hydrogen flow, 0.12 pound per hour (0.05 kg/hr); initial inlet-stream humidity, 2.0.

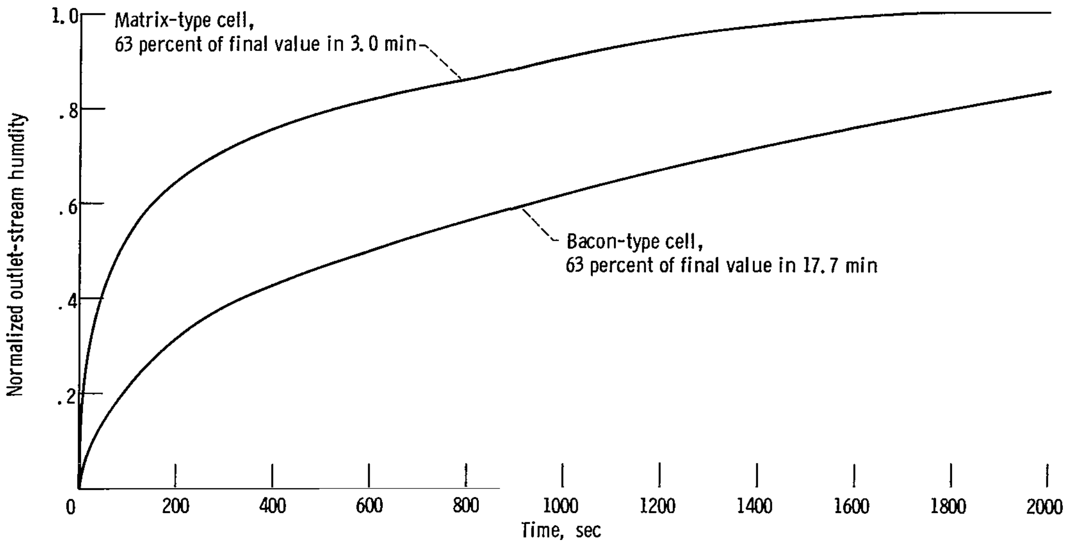



Figure 13. - Comparison of transient outlet-stream humidity response of matrix- and Bacon-type cells (ref. 1) for step increase in inlet-stream humidity.

in this figure the matrix-cell response attains 63 percent of its final value in 3 minutes while the Bacon-cell response reaches 63 percent of its final value in 17.7 minutes, this being the time constant of the Bacon-cell response.

The controlling factors in the increased response can be qualitatively determined by applying the Bacon-cell model to the matrix cell. By substituting the various operating parameters of the transients shown in figure 13 into the mathematical model, the response for these cases was calculated. From these calculations, it was found that the factors controlling the increase in the response speed of the matrix cell were its relatively high ratio of total hydrogen flow to hydrogen consumption, which is an operating parameter, and its relatively small mass of electrolyte, a characteristic of the matrix cell. These factors contribute equally to the increased response speed.

## Load Current Steps

The general character of the cell outlet water-vapor flow response to step increases in the rate of water production (load current) is illustrated in figure 14. The overshoot of the water-vapor flow rate above its final steady-state value eliminates the possibility of using the first-order theory developed for the Bacon cell to simulate the matrix-cell water-rejection mechanism for transients of this type. In figure 14, the shaded area above the final steady-state flow rate represents a decrease in the water content of the electrolyte, while the small shaded area below the steady-state value represents an increase of water in the electrolyte. This effect is also in evidence in figure 5 as the

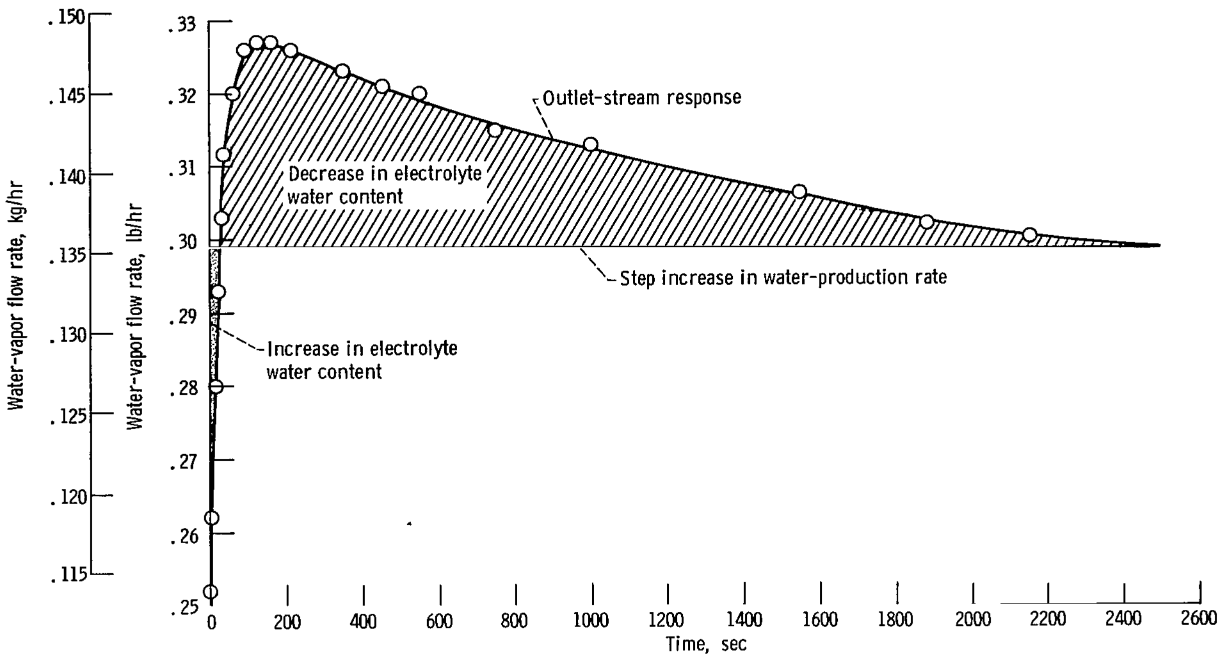



Figure 14. - Transient response of water-vapor flow rate of cell outlet stream to step increase in load current (rate of water production). Operating conditions: load current step, 20 to 80 amperes; inlet-stream hydrogen flow, 0.12 pound per hour (0.05 kg/hr); inlet-stream humidity, 2.0.

small initial dip in the calculated concentration. The data of figure 14 depict a net removal of 0.0067 pound (0.003 kg) of water from the electrolyte which is equivalent to an increase of approximately 4 percent in the electrolyte concentration. The most extreme case tested was a water-production step of 0.06 pound per hour (0.03 kg/hr) (i.e., a current step from 20 to 100 A). This produced an increase of approximately 6 percent in electrolyte concentration.

The drying effect experienced during step load increase transients is assumed to be caused by accompanying temperature increases. Since cell temperature was not actively controlled, it could be expected to increase because of the greater waste-heat production rate that accompanies an increased current drain. The equilibrium water-vapor pressure above the electrolyte increases exponentially with temperature and is proportional to the concentration of water. A sudden elevation in temperature accompanied by an increased rate of water production might then be expected to cause a disproportionate increase in the vapor pressure. Since the driving force for water transport is proportional to the vapor pressure, a corresponding "overshoot" in the water-removal rate might occur, such as was evidenced. The Bacon cell of reference 1 did not display an overshoot in outlet-stream humidity because it was operated isothermally.

The drying effect that a load current step increase has on the cell electrolyte is decreased by increasing the humidity of the inlet stream. This is illustrated in figure 15

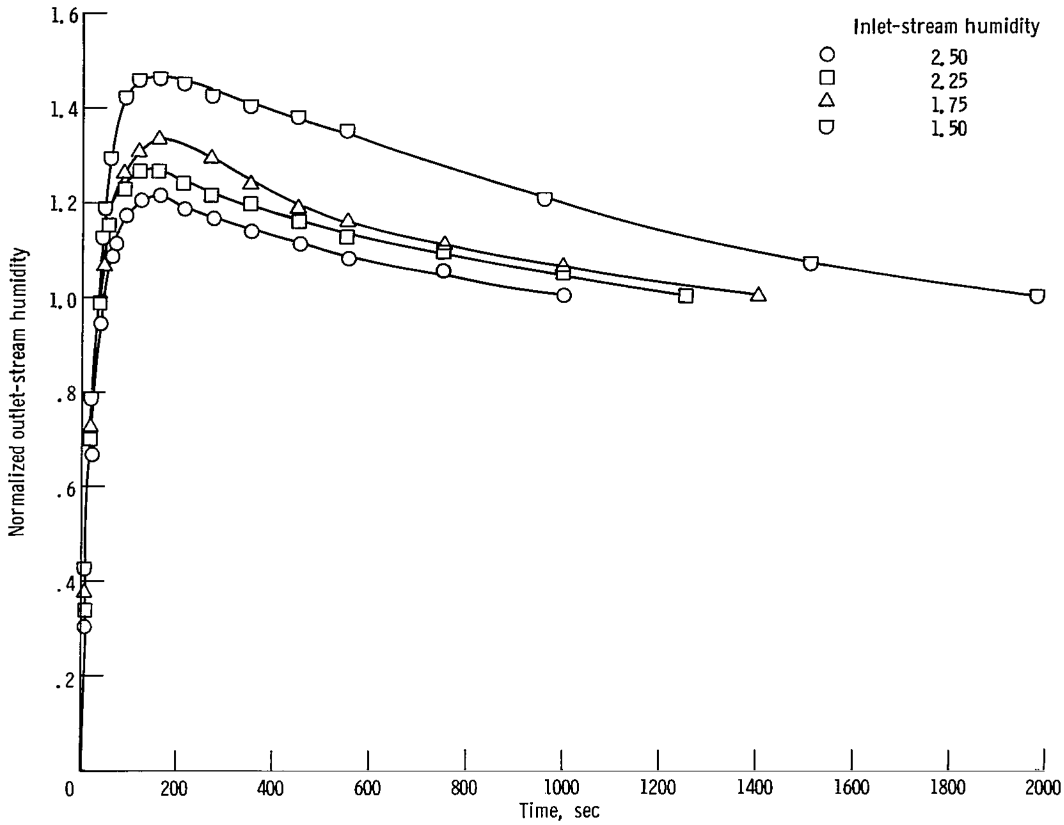



Figure 15. - Comparison of response of outlet-stream humidity to step increase in operating current for various inlet-stream humidities. Operating conditions: current step, 20 to 60 amperes; inlet-stream hydrogen flow, 0.12 pound per hour (0.05 kg/hr).

where, for the same load current step (20 to 60 A) and for the same inlet hydrogen flow rate, the normalized outlet-stream humidity response is plotted for four different inlet-stream humidities. A decrease of 35 percent in the peak overshoot in the outlet-stream response results from increasing the inlet-stream humidity from 1.5 to 2.5.

By decreasing the inlet-stream hydrogen mass flow rate while holding the stream humidity at a fixed value, the drying effect that a load current step increase has on the cell electrolyte is decreased. This is shown in figure 16. This figure shows four transient response curves for the same size load current step (20 to 60 A) with hydrogen-stream mass flows ranging from 0.12 to 0.18 pound per hour (0.05 to 0.08 kg/hr). This range of flows caused a decrease of 9 percent in the peak overshoot of the outlet-stream humidity.

Peak overshoot data for current steps of various magnitudes are shown in figure 17. Each step was introduced with the cell at the same initial operating conditions (current, 20 A; inlet humidity, 1.5). A straight line fits the data well, indicating the existence of a linear relation between the overshoot peak and current step magnitude. The increase in

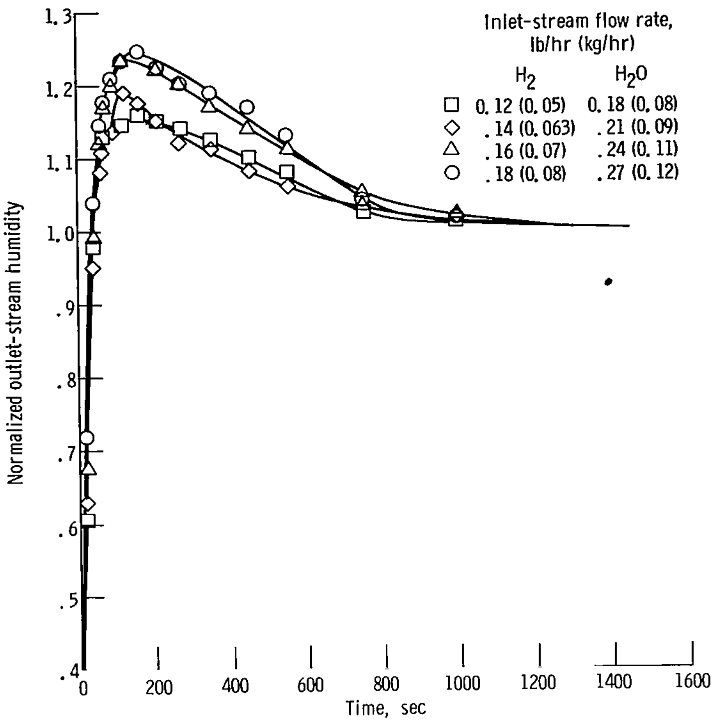



Figure 16. - Comparison of response of outlet-stream humidity to step increase in operating current for various inlet-stream flow rates. Operating conditions: inlet-stream humidity held constant at 2.0; load current step, 20 to 60 amperes.

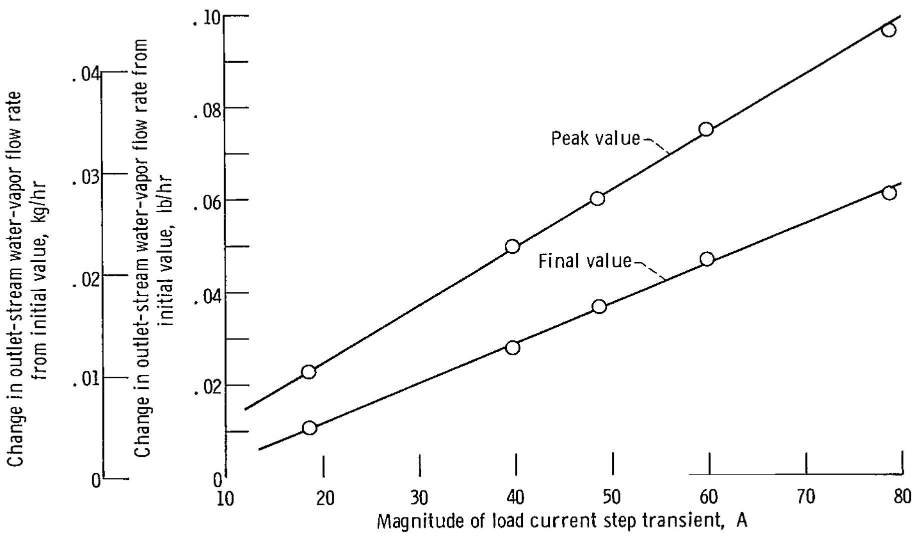



Figure 17. - Change in peak and final values of outlet water-vapor flow rate as function of magnitude of step transients in load current. Operating conditions: inlet-stream humidity; 1.5; inlet-stream hydrogen flow, 0.12 pound per hour (0.05 kg/hr); initial load current, 20 amperes.

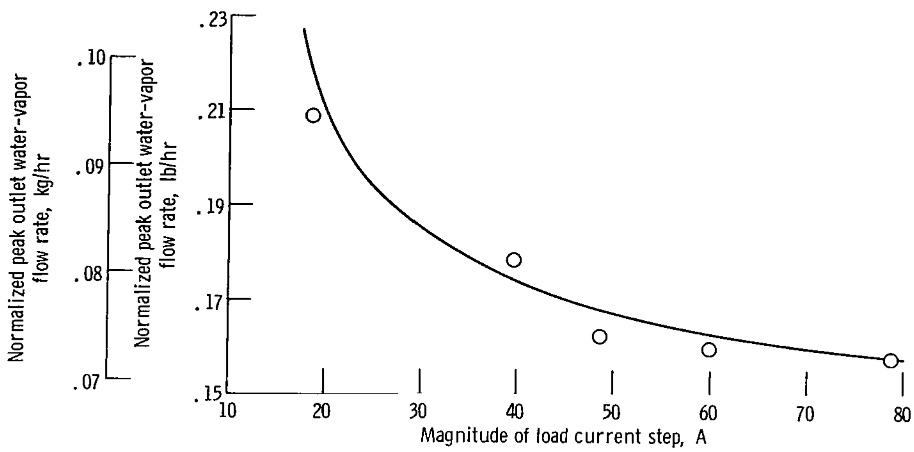



Figure 18. - Normalized peak outlet water-vapor flow rate against magnitude of load current step transient.

the difference between final and initial outlet water flow rate with current step magnitude is also shown in figure 17. By dividing the peak data points (upper line) by the final steady-state data points (lower line) of figure 17, normalized peak data were obtained and plotted in figure 18. (Taking ratios of points on the faired-in straight lines of fig. 17 provides the smooth curve of fig. 18.) This curve (fig. 18) identifies the water-rejection process for steps in cell current as being nonlinear.

## SUMMARY OF RESULTS

Tests of a matrix type of hydrogen-oxygen fuel cell using hydrogen recirculation for water removal produced the following results:

1. The response of the matrix-cell water-rejection mechanism to disturbances in hydrogen-stream inlet humidity was nearly linear, as indicated by the small deviation between normalized outlet humidity responses for inlet humidity steps of various magnitudes.

2. An increase in the cell initial load current, hydrogen flow rate, or hydrogen-stream inlet humidity resulted in an increase in the speed of response of the outlet humidity to step disturbances in hyrdogen-stream inlet humidity.

3. A linear first-order mathematical model developed for the water-rejection mechanism of a Bacon type of cell provides, at best, a rough approximation of the outlet humidity response of the matrix cell. Differences between comparable experimental and calculated response curves indicated that effects other than first-order would have to be included in a more complete mathematical model.

4. The matrix cell responded much faster than a Bacon cell tested previously.

The main factors contributing to the faster response of the matrix cell were its small amount of electrolyte and its high ratio of total hydrogen flow to hydrogen consumption rate.

5. For step increases in the rate of water production, which were obtained by step increases in load current, an overshoot of the final value occurred in the outlet humidity transient response. The overshoot, which represents a drying effect on the cell electrolyte, is probably the result of an increase in the temperature of the electrolyte that accompanies a load current increase. Because of the overshoot, the first-order mathematical model developed for the water-rejection mechanism of the Bacon cell does not adequately simulate the response of the matrix cell for load step transients.

6. The overshoot in the outlet humidity response to step changes in load current varied in a manner that indicated the water-removal mechanism was nonlinear for changes in water-production rate. The amount of overshoot in the outlet humidity response and its attendant electrolyte-drying effect are a function of the hydrogen-stream inlet conditions. Increasing the inlet-stream humidity at a fixed hydrogen flow decreases the overshoot, while increasing the inlet-stream flow rate at a fixed humidity increases the overshoot.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, September 19, 1968,
120-34-02-24-22.

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